WEAR PROGRESS OF EXCHANGEABLE CUTTING INSERTS DURING TI_6AL_4V ALLOY MACHINING

PETRŮ Jana, SCHIFFNER Jan, ZLÁMAL Tomáš, ČEP Robert, KRATOCHVÍL Jiří, STANČEKOVÁ Danka

VSB - Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Machining, Assembly and Engineering Metrology, Ostrava, Czech Republic, EU

Abstract

This article deals with experimental determination of cutting tool wear during machining of Ti_6Al_4V alloy. This alloy features worsened machining ability that has direct influence on wear intensity and durability of cutting tool during machining. Worsened machining ability usually negatively demonstrates itself by lowered quality of machined surface and subsurface layers of the material. The experimental part was focused on measuring of amplitude and progress of the tool cutting edge wear during machining of Ti_6Al_4V material. The amplitude of the tool - exchangeable cutting inserts with deposited PVD layers - wear was determined by direct measurement of linear dimensions according to the ISO 3685:1993 standard.

Keywords Cutting process, inserts, sintered carbide, wear

1. INTRODUCTION

Development in the area of Titanium and its alloys machining unequivocally leads to verification and testing of cutting tool suitable materials and parameters of the cutting process. Titanium is harder to machine in comparison with other metallic materials. Increased loads on the tool - machine system, short tool shelf life, quality of machined surface, changes in micro hardness and mechanical hardening of machined surface are demonstrations of this worse machine ability of Titanium that are not occurring on such scale during machining of more usual steels. Titanium alloy machining is highly problematic and many experts published contributions in this sense that are listed in the world wide accepted Scopus and Web of Science databases.

Cutting speeds slower than 60 m/min in combination with slow feed rate are recommended for machining of Titanium alloys as described in the article Obrabanietitanovychniklovychzliatin (Machining of Titanium Nickel Alloys) by M. Neslusan and A. Czan. [1] A build-up occurs on the tip of cutting tool during machining of a Titanium alloy, which leads to unstable cutting process and premature cutting tool wear. Significant majority of tool materials have a tendency to react chemically with Titanium, as soon as the temperature in the cut location exceeds the value of 510°C [2]. Low heat conductivity of Titanium alloys is usual reason for occurrence of high temperatures in the cutting tool and machined piece contact zone. About 80% of originating heat transfers into material of the tool during machining of Ti_6Al_4V alloy. High temperature in the cut location is the main factor that causes excessive wear of the tool. [2]

The Ti_6Al_4V alloy specifically keeps its hardness and strength during increased temperatures, which also contributes to intense wear of the tool. During machining of this Titanium alloy the tool material is exposed to significant mechanical and heat stresses that are focused along the whole length of the tool cutting edge during the stroke.

The machining of difficulty to cut materials causes problems in terms of the required quality and overall effectiveness of the process. A number of works have been published which indicate that the subjects of interest are still important [9, 10, 11, 12].

Worsened Titanium alloy machining ability is caused especially by the following aspects: [1]

- High heat stress on the VBD cutting edge - by combination of low heat conductivity and high heat absorptive capacity about 30% more heat must be absorbed by the cutting edge in comparison with more usual machining of steel. The temperature during machining of Ti_6Al_4V is about twice as high. Diffusion and adhesion processes are thus more pronounced, and there is a high temperature gradient that creates a heat tension.
- High pressure on the tool cutting edge caused by smaller contact area - this phenomenon is caused especially by low plasticity of Titanium alloys and it gets worse with increasing cutting speeds due to smaller angle of the shear plane.
- Mechanical load - oscillating loads are caused by the process of articulated chip creation that is caused by high strength of the material while heated.
- Vibrations of the machining system - the combination of Young's modulus of elasticity with high shear limit especially allows occurrence of small plastic deformations. The material is elastic and flexibly resists cutting stresses. This leads to lowering of effective angle on the flank face. The friction in contact zone increases, which causes vibrations. High cutting strengths and low frequencies caused by relatively low revolutions also support occurrence of vibrations.
- Diffusion wear - there is a tendency of Titanium to react with surrounding elements, which causes softening of cutting material.
- Adhesion wear - high tendency for adhesion is caused by increasing temperature in the cut location.

2. EXPERIMENTAL MACHINING OF TITANIUM ALLOY

The experimental part of the work was done to evaluate suitable exchangeable cutting inserts for machining of the Ti_6Al_4V alloy. The evaluation criterion for the proposed exchangeable cutting inserts during machining was the amplitude of wear and total durability of the tool cutting edge. Three exchangeable cutting inserts with deposited PVD layers with different chemical compositions were proposed for experimental machining of the Titanium alloy. Measuring of cutting edge wear took place after elapsing of set intervals up to the predetermined wear value VB. Wear amplitudes were determined by direct measurements of linear dimensions using a Carl Zeiss Jena optical microscope.

2.1. The Ti_6Al_4V Titanium Alloy

This Ti_6Al_4V alloy belongs to the ISO S material group. This Titanium alloy is the most common alloy that covers up to 50 % of the total Titanium use in the industry. Thanks to its unique properties it is widely used in aircraft, automotive, biomedical and other industries. It is commonly used in operation temperatures around 350 °C. When oxygen or water act on this material an immediate stable, continuous and firmly attached oxide coating is spontaneously created on the surface of the material. It is just this coating that is responsible for its outstanding resistivity against corrosion in various aggressive environments. The Ti_6Al_4V alloy is highly resistant against areal corrosion in water solutions, as well as in oxidation acids, chlorides, fuels and alkalis. [3]

Table 1 Chemical composition of the Ti_6Al_4V alloy

Element	C	Fe	Al	V	Ti
Mass [%]	0.10	0.4	5.5 - 6.75	3.5 - 4.5	Remainder

Table 2 Mechanical and physical properties of the Ti_6Al_4V alloy

Mechanical properties		value	Physical Properties		Value
Yield limit $R_p0.2$	MPa	950	Density ρ	g/cm^3	8.4
Hardness HB	-	326	Specific heat c_p	J/g.°C	526
Strength limit R_m	MPa	1020	Heat conductivity λ	W/m.K	6.7
Ductility A	%	15			

Structure of the Ti_6Al_4V Titanium alloy consists of crystal hexagonally arranged lamellar α-phase and β-grains of 0.4 μm size. At the temperature around 890 °C Titanium goes through allotropic transformation to β cubic phase that remains stable till the melting temperature. [3]

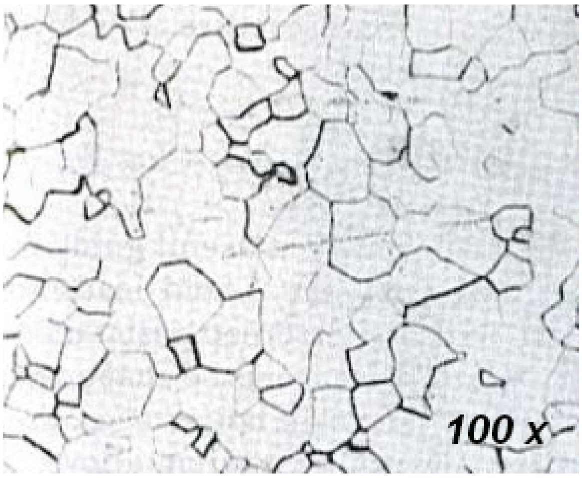


Fig. 1 Structure of the Ti_6Al_4V Titanium alloy (magnified 100 times) [4]

2.2. Selection of Tools and Cutting Geometry

Tool manufacturers recommended exchangeable cutting inserts for Titanium machining. It is suitable to use insertss made from coated sintered carbide, especially the ones with higher Cobalt content and fine-grained structure. Cutting inserts marked and cutting geometry CNMG 120408 were used for straight turning of Ti_6Al_4V Titanium alloy, see **Fig. 2** that had been coated by the PVD method to improve its useful properties and resistivity against wear.

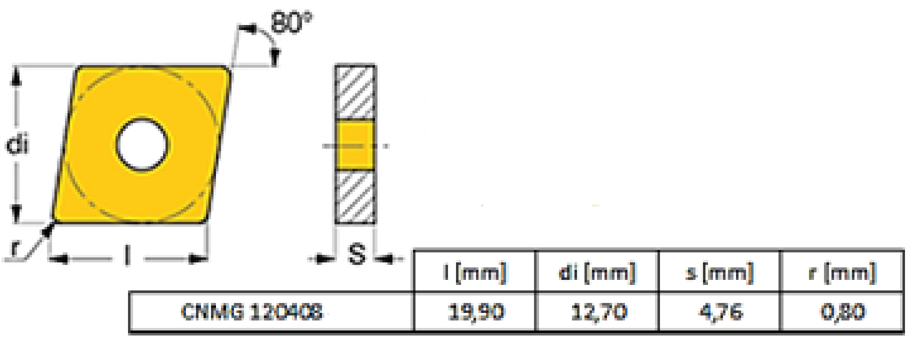


Fig. 2 Geometry of the exchangeable cutting inserts [5]

The following exchangeable cutting inserts were used to machine the Ti_6Al_4V Titanium alloy:

CNMG 120408 - SM

T8315 - materials stand from combinations of submicron tungsten carbide alloys with different content of cobalt binder phase. Applied PVD coating is based on nanostructured gradient TiN/TiAIN composition.

CNMG 120408 - M5

9605 - The insert material is innovative submicron substrate with TiAIN coating deposited by PVD method against oxidation.

CNMG 120408 - NRS

WSM20 - The insert material consists of strenuous submicron substrate with PVD method deposited coating of Aluminum oxide Al_2O_3

Setting of Cutting Parameters:

Due to low heat conductivity and intense mechanical loads on tool cutting edge low cutting speed and feed rate were proposed for machining of the Ti_6Al_4V Titanium alloy.

Cutting Speed, v_c = 44 m/min

Feed Rate, fn = 0.25 mm

Depth of Cut, a_p = 2 mm

3. MEASURING AND DETERMINATION OF CUTTING INSERT WEAR

Together with measuring of the progress of the cutting insert wear the amount of material cut-off the surface of test sample was determined. 66000 mm^3 of material was taken off under given cutting conditions during each measurement of the tool wear. The amplitude of wear on the flank face VB_{opt} 500 μm was set as the wear criterion. In comparison to machining of Nickel alloys, where the main demonstration of the wear was creation of a notch on the flank face, intense tool wear in the area of the tool tip VB_C occurred here and also a groove was created on the rake face.

Volume of the cut-off material - V [mm^3]

$$V = v_c \cdot a_p \cdot f \cdot \mathrm{t}_{\mathrm{As}} / 10^3 \qquad (1)$$

v_c - cutting speed [m/min],

a_p - depth of cut [mm],

f_n - feed rate [mm],

t_{Aas} - machine time [min].

It is apparent from the results and progress of the tests, that during machining of the Ti_6Al_4V Titanium alloy the critical factor for the tool durability of an exchangeable cutting insert is definitely resistivity against high temperatures and wear in the form of a groove on rake face. After reaching predetermined wear criterion and loss of tool durability there was occurrence of the groove at the rake face and very intense plastic deformation of the cutting edge.

Amplitude of the flank wear in the area of the tool tip VB_C and the wear in the form of a groove on the rake face of inserts can be easily seen in the below photo documentation. The highest durability during machining of the Ti_6Al_4V Titanium alloy was demonstrated by exchangeable cutting inserts with T8315 and 9605 coatings.

Table 3 Wear of the tool cutting edge

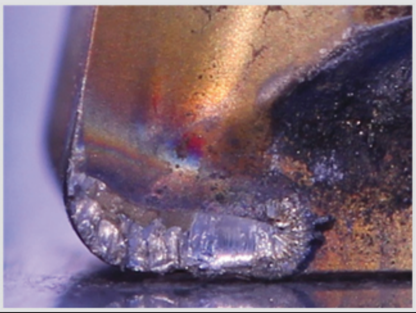
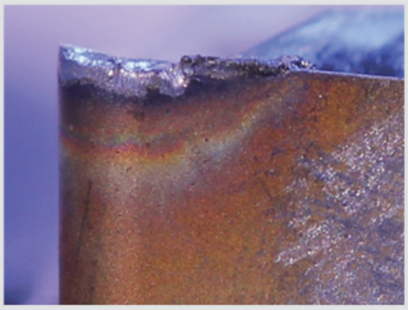
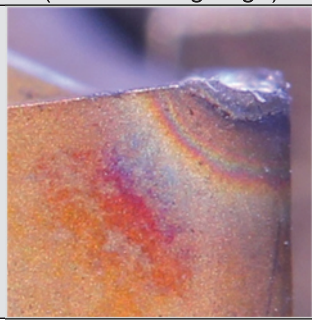
CNMG 120408-SM, T8315		
t_{As} = 14 min		VB_C = 410 µm
Rake face	Flank face (major cutting edge)	Flank face (minor cutting edge)
		

Table 4 Wear of the tool cutting edge

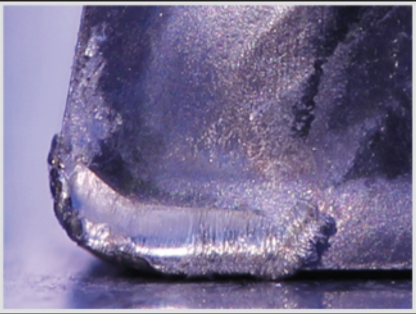
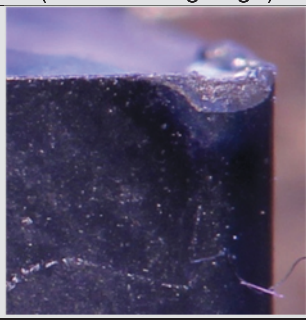
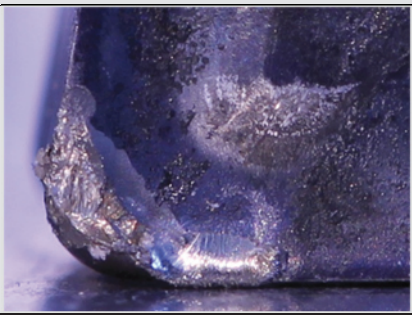
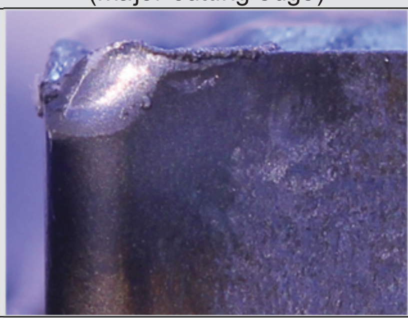
CNMG 120408-M5, 9605		
t_{As} = 14 min		VB_C = 655 µm
Rake face	Flank face (major cutting edge)	Flank face (minor cutting edge)
		

Table 5 Wear of the tool cutting edge

CNMG 120408-NRS, WSM20		
t_{As}= 9 min		VB_C = 810 µm
Rake face	Flank face (major cutting edge)	Flank face (minor cutting edge)
		

Durability of cutting edges was, under given cutting conditions of this test, proportional to the tool cutting edge durability against high temperatures and resistivity against creation of a crater on the rake face. Thus a negative cutting geometry of the inserts may not be best for longer durability of cutting edges during machining of Titanium alloys, since it leads to creation of higher amount of heat in the cut location.

From the point of view of exchangeable cutting insert wear was found that there is a change in creation of chips just before destruction of the cutting edge (caused by exceeding of cutting capacity of the cutting edge). A short segmented chip is created before exceeding the cutting capacity limit; after this a long spiral chip occurs. When creation of this long spiral chip occurs there is only several tens of seconds before cascading destruction of the cutting edge. Due to this phenomenon measurements of cutting edge wear had to be stopped just before achieving the VBopt wear criterion value.

Another factor that leads to premature destruction of the exchangeable cutting inser is the distance of a crater from the secondary cutting edge, see **Fig. 3**. In this location there are huge heat and strength loads of originated "bridge" in the case of critical distance and depth of the crater. These loads cause breakdown of this bridge and cascading wear of the tool cutting edge, see **Fig. 3**.

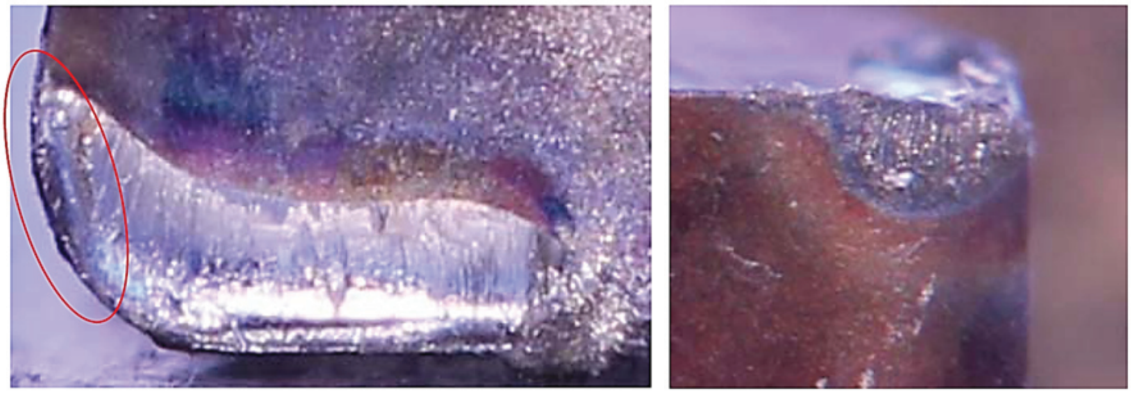


Fig. 3 The example of the distance of the crater on the rake face and the secondary cutting edge (left), the example of breakdown of the exchangeable insert secondary cutting edge (right)

3.1 Determination of the Tool Durability

In order to determine the amplitude of tool cutting wear the wear in the area of tool tip, where the tool is worn the most intensively, was measured during machining of the Ti_6Al_4V Titanium alloy. VB_{opt} 500 µm was set as the wear criterion for determination of the insert durability. Also the width of a crater on the rake face KB was measured after the set interval together with the measurement of the amplitude of tool flank wear progress.

Table 6 The tip wear - VB_C values

CNMG120408-SM		CNMG 120408-M5		CNMG120408-NRS	
t_{As} [min]	VB_C [µm]	t_{As} [min]	VB_C [µm]	t_{As} [min]	VB_C [µm]
4.00	138	4.00	87	4.00	138
8.00	141	8.00	93	8.00	201
12.00	198	12.00	100	10.00	825
14.00	219	14.00	146		
16.00	407	16.00	649		

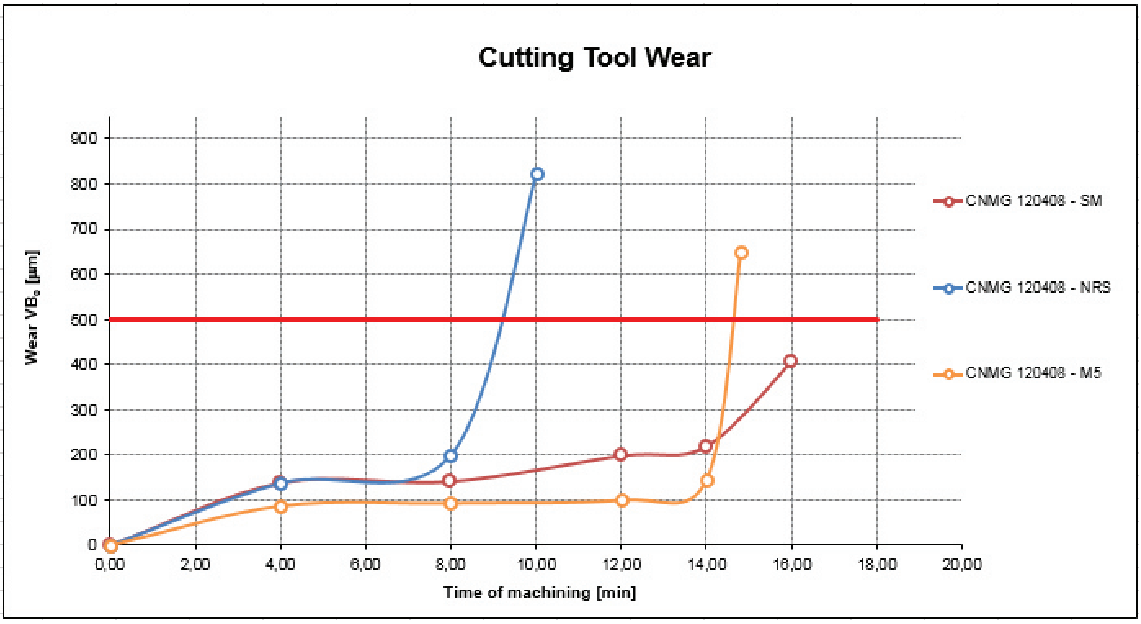


Chart 1 The progress of wear at the area of tool tip VB_C

Table 7 The crater width - KB values

CNMG120408-SM		CNMG 120408-M5		CNMG120408-NRS	
t_{As} [min]	KB [µm]	t_{As} [min]	KB [µm]	t_{As} [min]	KB [µm]
4.00	939	4.00	910	4.00	926
8.00	945	8.00	1009	8.00	1036
12.00	943	12.00	1023	10.00	1272
14.00	975	14.00	1024		
16.00	980	14.80	1025		

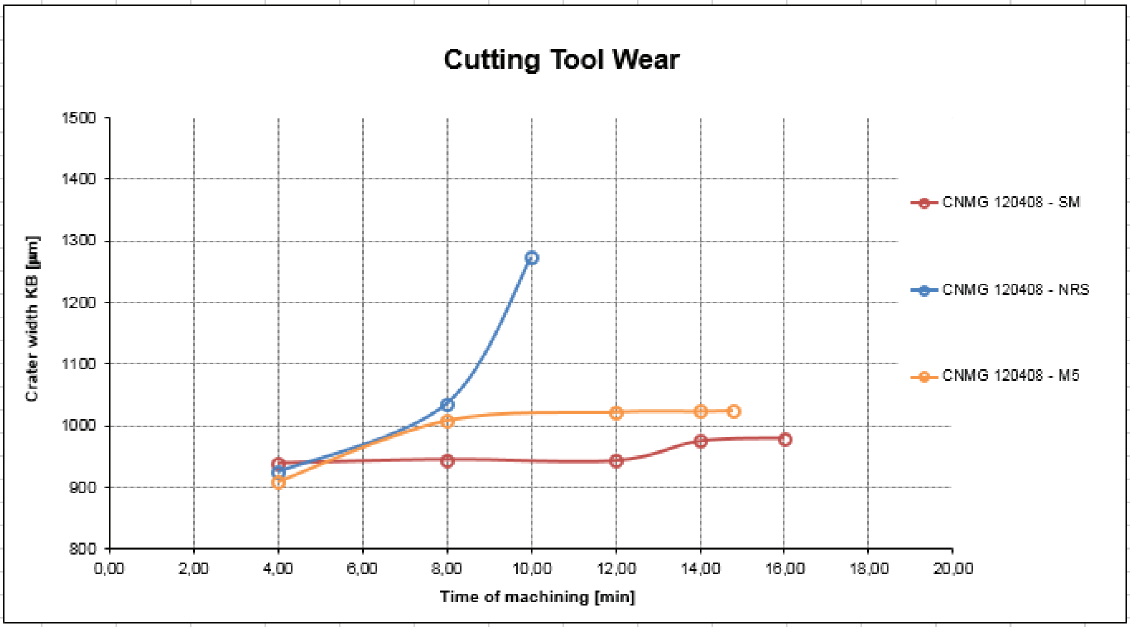


Chart 2 The wear progress - a KB crater width

4. DISCUSSION OF RESULTS AND RECOMMENDATIONS

It is apparent from the exchangeable cutting insert wear measurement results, that during machining of the Ti_6Al_4V Titanium alloy, the critical demonstration of the cutting edge is the wear in the area of the tool tip VB_C. The wear in the area of the tool tip was caused primarily by machining of the strengthened layer of material, where the tip of the cutting edge is exposed to the combination of very intensive mechanical and heat loads.

The worst results during machining of Titanium alloy were reached by the CNMG 120408 - NRS exchangeable cutting insert with WSM20 coating. The critical wear value VB_C = 500 μm at the tip area was reached within 9 minutes. Durability of this cutting tool can be achieved by modification of cutting conditions or by proper selection of abrasion resistant base and coating always in combination with a suitable cutting geometry of the tool. The best results were achieved with the CNMG 120480 - SM cutting tool with T8315 coating and the CNMG 120408 - M5 tool with 9605 coating. Durability of these cutting tools under given cutting conditions was around 14 minutes. However, wear in the tip area was more intensive with the CNMG 120408 - SM cutting tool with T8315 coating, which could have been caused by the combination of basic base material and coating substrate or by their chemical composition.

Beyond chemical composition of the substrate and deposited coating the durability of the tool during machining of Titanium alloys can be extended by a change of cutting tool geometry for example. It is advantageous to use positive geometry with the angle of main cutting edge of 45° for machining of Titanium alloys. Also round (large radius) inserts are suitable for machining of Titanium alloys, where the angle of main cutting edge can be changed depending on the depth of machined material. By employing a round inserts a machining feed rate can be increased and required roughness of the machined surface can be achieved at the same time. [7] However, the amount of heat at the cut location increases with increasing feed rate. This is a critical parameter for using sintered carbide tools that are not capable of resisting to high temperatures. A solution could be employing of ceramic or cubic Boron nitride cutting tools that resist high temperatures more easily and have higher resistance against wear. [8]

5. CONCLUSION

Although Titanium alloys belong to, thanks to their specific properties, hard to machine materials, they can be easily and effectively machined under certain cutting conditions. Bad machining ability of Titanium is primarily caused by low heat conductivity of the material that is the reason for extensive heat loads of the tool cutting edge. It is apparent from the performed tests that it is possible to use even sintered carbide tools for machining Titanium alloys that, thanks to deposited coating, have increased resistivity against abrasion and especially higher temperatures. However, their durability was limited during machining of Titanium alloys and it was not quite effective under given cutting conditions. Exchangeable cutting edge inserts were exposed to very intensive mechanical and heat loads during machining of the Ti_6Al_4V Titanium alloy. This was the reason for the wear in the area of the tool tip VB_C. Increased cut resistance and increased temperature resulted in tip plastic deformation and cascading destruction of the cutting edge.

Tool wear is an integral part of the machining process that cannot be avoided. However, it can be safely monitored and controlled by proper selection of cutting process, change of cutting material and tool geometry or by modification of cutting conditions in order to minimize the influence of tool wear on the quality of machined surface, shape and dimensional accuracy of machined parts and safety of the whole machining process.

ACKNOWLEDGEMENTS

Article has been done in connection with project Increasing of Professional Skills by Practical Acquirements and Knowledge, reg. no. CZ.1.07/2.4.00/17.0082 supported by Education for Competitiveness Operational Programme financed by Structural Founds of Europe Union and from

the means of state budget of the Czech Republic and by project Integrita No.CZ.1.07/2.3.00/20.0037 and Student Grant Competitions SP2015/116 and SP2015/129.

REFERENCES

[1] NESLUSAN, M., CZAN, A. Obrabanie titanovych a niklovych zliatin. Zilina: Zilinska univerzita v Ziline / EDIS, 2001. 189 pp. ISBN 80-7100-933-4.

[2] CAMPBELL,F.C. Manufacturing Technology for Aerospace Structural Materials 1.vyd. Elsevier Ltd., 2006. 617 pp. ISBN 1-85-617-7495-6.

[3] Slitiny titanu. Ti_6Al_4V. [online]. [cit. 2015-03-24]. Available from WWW: <http://cartech.ides.com/datasheet.aspx?i=101&E=269&FMT=PRINT>.

[4] Microstructure Ti_6Al_4V. [online]. [cit. 2015-03-24]. Available from WWW: <http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BAR0-0030-0032>.

[5] Modern Metal Cutting, A practical Handbook, SandvikCoromant, ISBN 91-972299-4-6.

[6] ISO 3685:1993 (1993). Tool-lifetestingwith single-point turningtools. Geneva, International OrganizationforStandardization, 48 pp.

[7] PETRU, J., PETRKOVSKA, L., ZLAMAL, T., MRKVICA, I. Resistance of Sintered Carbide Materials against Heat Shocks Induced by Cutting Process. In METAL 2014 Conference Procedings of the 23Rd International Conference on Metallurgy and Materials, Czech Republic, Brno May 21st - 23rd 2014. Ostrava: TANGER Ltd., 2014, 1st edition, pp. 1 - 6 + proceedings on CD. ISBN 978-80-87294-52-9.

[8] PETRU, J., ZLAMAL, T., CEP, R., PAGAC, M., GREPL, M. Influence ofStrengtheningEffect on MachinabilityoftheWeldedInconel 625 and oftheWroughtInconel 625. In IMETI 2013 Procedings of the 6th International Multi-Conference on Engineering and Technological Innovation, USA, Florida, Orlando, 9th - 12th July 2013. Orlando: International Institute of Informatics and Systematics, 2013, 1st edition + proceedings on CD, pp. 1-5.

[9] KRÓLCZYK, G., GAJEK, M., LEGUTKO, S. Effect of the cutting parameters impact onto tool life in duplex stainless steel turning process. In TehničkiVjesnik - Technical Gazette, 20, 4 (2013), pp. 587- 592.

[10] MICHALIK, P., ZAJAC, J., HATALA, M., MITAL, D., FECOVA, V. Monitoring surface roughness of thin-walled components from steel C45 machining down and up milling. In Measurement: Journal of the International Measurement Confederation, 2014. Vol. 58, pp. 416-428. ISSN 0263-2241.

[11] STANCEKOVA, D., SEMCER, J., SAJGALIK, M., JANOTA, M. Heat-Affected Zone of Plasma of Laser Cut Materials. In Manufacturing Technology, 3/2014, pp. 451 - 456, ISSN 1213-2489.

[12] NAPRSTKOVA, N., CAIS, J., STANCEKOVA, D., Influence of Alsi7Mg0.3 alloy modification by Sb on the tool wear. In Manufacturing Technology, 1/2014, pp. 75 - 79, ISSN 1213-2489.